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DESIGN PROPERTIES OF RANDOMLY REINFORCED FIBER/RESIN COMPOSITES

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ABSTRACT

The pseudoisotropic laminate analogy is used in conjunction with fiber composite micro and macromechanics to predict the thermal and mechanical properties of planar randomly reinforced fiber composites (PRRFC). Theoretical results are presented for boron/epoxy, Thornel-50/epoxy, and S-glass/epoxy PRRFC. The results show that the thermal and elastic properties depend on both constituent materials and the fiber volume ratio (FVR). The strength depends also on the type of applied stress.

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INTRODUCTION

Planar randomly reinforced fiber composites (PRRFC) are of interest in certain structural application because they offer two primary advantages: (1) they provide stiffness, strength and hardness (in the macro sense) for multiple load directions at considerable weight savings over conventional materials; (2) they offer ease of fabrication of complex components. Some examples are jet engine air splitters and seals, gears, wheels, brakes, and pump housings. Another indirect but important advantage has to do with the production costs of fibers and prepreg tape. That is, defective runs and/or remnants from continuous tape production can be used effectively and efficiently to fabricate randomly reinforced composites.

Thermal and mechanical characterization of random composites are required to design structural components from these materials. The characterization can be done in at least four ways: (1) test (refs. 1 and 2); (2) statistical averaging of fiber distribution (refs. 3 to 5) or interfiber bond (ref. 6); (3) integration of unidirectional properties (refs. 7 to 10 and author's unpublished notes); and (4) the pseudoisotropic (quasiisotropic) laminate analogy (refs. 11 to 13). The first requires an extensive and perhaps cost-prohibitive amount of testing. The second usually leads into complex mathematical formalisms with some inconsistencies (ref. 4). The third might require certain approximations (ref. 10) or numerical integrations (ref. 8) and neglects the adjacent material contributions. The fourth is the most versatile because it is applicable to all thermal and all mechanical properties. And, in addition, it draws on the extensively developed technologies for micromechanics and laminate analyses. It is perhaps the most natural since the fibers have to be of considerable length for efficient utilization (ref. 14).

The potential of the pseudoisotropic laminate analogy for characterizing PRRFC has not been fully recognized in the fiber composite technology community as yet. Its useage has been limited to the prediction of some elastic and some thermal constants for a few specific composites (refs. 12 and 13).

It is the objective of this investigation to use the pseudo-isotropic-laminate analogy in conjunction with micro- and macromechanics to characterize PRRFC. The characterization consists of the thermal elastic and strength properties of several typical composites. These properties are presented in graphical form as a function of fiber volume ratio. Results for impact resistance and lamination residual stresses are also presented. References are cited where the correspondence between pseudoisotropic-laminates and PRRFC is theoretically examined.

THEORETICAL CONSIDERATIONS

Planar randomly reinforced fiber composites (PRRFC) and pseudoisotropic (quasiisotropic) laminates are thermoelastically isotropic in their plane. They are said to be thermoelastically equivalent. It is this equivalence which enables one to use laminate theory to characterize planar randomly reinforced composites. This is referred to as the "pseudo-isotropic laminate analogy." A brief description of the procedure follows:

Possible ply orientation combinations which will yield pseudoisotropic elastic behavior are described in reference 15 in the terms of n-fold symmetry lines. The simplest orientation combination for example, is a [0, +60, -60] laminate. This laminate lacks reflection-about-a-plane symmetry and will bend upon stretching, thus yielding erroneous measured data. The difficulty is overcome by constructing a laminate with the following combination of ply orientations [0, +60, -60, -60, +60, 0]. Application of laminate theory (ref. 16) to this laminate yields its thermoelastic properties. Such predictions are in good agreement with experimental data. (See, e.g., ref. 17, pp. 161 and 173.) The aforementioned laminate is not pseudoisotropic with respect to strength. That is, the laminate's strength will depend on both load direction, say with respect to 0^{o}-plies, and also to the type of load, for example, tensile, compressive, or shear. It can be shown theoretically (author's unpublished notes) that the [0, +60, -60, -60, +60, 0] laminate will have both a minimum and a maximum strength. The minimum is obtained when the load direction coincides with one of the ply orientations and a maximum when the load direction bisects the angle of two adjacent ply orientations.

It can be shown both theoretically and by numerical computation that the minimum strength of pseudoisotropic laminates as defined in reference 18 is independent of the number of ply orientation combinations. This is an important finding since it provides a lower bound on the strength of pseudoisotropic laminates. It can be shown by numerical computation that the maximum strength of pseudoisotropic laminates approaches a lower bound as the number of ply orientation combinations increases.

This is illustrated graphically in figure 1 where the failure stress is plotted as a function of the number of plies for several pseudoisotropic laminates.

A PRRFC is, in essence a pseudoisotropic laminate with a large number of ply orientation combinations. Therefore, the PRRFC's strength must be equal or greater than the strength lower bound of pseudoisotropic laminates. The establishment of this condition enables us to utilize fiber composite micro and macromechanics and laminate theory to predict the thermal, elastic, and strength properties of PRRFC. In the subsequent discussion the terms pseudoisotropic and random will be used interchangeably.

The numerical results to be presented and discussed herein were generated using the computer code of reference 16. This code generates ply and laminate properties from input constituent properties. Code generated unidirectional composite properties of the composite systems investigated are shown in table I for one fiber volume ratio (FVR). The strength of the pseudoisotropic laminate was taken to be equal to the applied stress which produced failure in at least one of the plies as predicted by the combined-stress failure criteria described in reference 18.

Comparisons of the strengths of some random composites with some special composites are instructive. In figure 2, the pseudoisotropic composite strength is compared with the uniaxial strength of Thornel-50S/epoxy composites. The results are plotted as a function of fiber content. As can be seen in this figure the strengths of the pseudoisotropic composites lie between the transverse and the longitudinal strengths of the unidirectional composites and depend on the type and sense of applied stress. It should be noted that the random composite tensile or compressive strength averages about one third of the corresponding unidirectional composite longitudinal strength. However, the shear strength of the random composite is about 50 percent of its tensile strength. This percentage is approximately the same for isotropic homogeneous ductile materials. Comparisons of random composite strength with special composites are shown in figure 3 as a function of load angle. As can be seen in this figure random composites are stronger than some directional composites for certain load angles.

RANDOM COMPOSITE CHARACTERIZATION DATA

Using the computer code of reference 16, characterization data was generated for the following three composite systems: boron/epoxy, Thornel-50S/epoxy, and S-glass/epoxy. The characterization data includes weight density, thermal and elastic properties and strength as a function of fiber volume ratio. Data for residual stresses and impact energy density are also included. The weight density of the three composite systems is shown in figure 4 as a function of fiber volume ratio.

Thermal Properties

The heat capacity of the three random composite systems is shown in figure 5 as a function of fiber volume ratio. The corresponding heat conductivities for inplane and through-the-thickness heat transfer are shown in figures 6 and 7, respectively. In heat transfer analyses both of these heat conductivities are required since it is possible to have heat flowing through the plane and through thickness of the composite. It is interesting to note that the inplane heat conductivities for the random composite are the algebraic averages of the longitudinal and transverse heat conductivities. Compare corresponding values from table I and figure 6. This observation agrees with the results obtained by the integration method (author's unpublished notes).

The thermal coefficients of expansion are plotted in figure 8 as a function of FVR for the three random composite systems. It is noted in passing, that these results are smaller in general than those obtained by the integration method. The results predicted by the integration method are the algebraic average of longitudinal and transverse values. The reason for the discrepancy is that the integration method does not account for the restraint provided by adjacent plies. The unrestrained condition assumed with the integration method is not compatible with the physical situation of PRRFC. Even the use of the finite element method as described in reference 19, while representative for the ply, needs implementation to account for adjacent ply restraining effects.

Elastic Properties

The normal modulus is plotted in figure 9 as a function of the FVR for the three random composite systems. Analogous results for shear modulus and Poisson's ratio are plotted in figures 10 and 11, respectively. It can be verified by direct substitution that corresponding FVR results from figures 9, 10, and 11 satisfy the isotropic material elastic constants condition: $E = 2(1 + \nu)G$.

It is noted that elastic constant values obtained by integration (refs. 8, 9, and author's unpublished notes) do not always satisfy this condition. The statistical methods proposed in references 3 and 4 fail to satisfy the isotropic elastic materials condition. It can be seen in figure 12 that the Poisson's ratio varies slightly with fiber volume ratio. The approximate one-third ratio of $E_{c}/E_{\ell 11}$ applies to these composites as can be verified from the results of table I and figure 10.

Strength Properties

In the following strength calculations, both the void and residual stress effects were neglected. These effects can be easily investigated using the computer code of reference 16. The magnitude of the residual stresses is treated in a separate section.

Failure stresses (strengths), obtained as described in the section Theoretical Considerations, are shown in figure 12 as a function of FVR for a Thornel-50/epoxy random composite. As can be seen the strengths are for applied tensile, compressive, and shear stresses. Corresponding results for Thornel-50S (treated fiber)/epoxy are shown in figure 13. A significant point is observed by comparing corresponding FVR results from figures 12 and 13. This comparison shows that the treated fiber composites have compressive and shear strengths about twice those of the untreated fiber, and also a 15 percent increase in the tensile strength. This increase in strength is a result of increases in the ply transverse tensile and intralaminar shear strengths of the treated fiber composite. A point to be made at this juncture is the following: Statistical methods which assume that either the fiber (ref. 4) or the interfiber bond (ref. 6) supply all the strength in PRRFC cannot account for the increase in strength shown by the treated fibers.

An additional important point to be made is the significant difference between the tensile and compressive strengths. This significant difference is reported here for the first time. It can neither be predicted by the statistical methods proposed in references 3, 4, and 6, nor by the integration method suggested in reference 10. The reason these methods cannot predict the significant difference in tensile and compressive strength is that they do not account for the five distinct strengths ($S_{\ell 11T}$, $S_{\ell 11C}$, $S_{\ell 22T}$, $S_{\ell 22C}$, $S_{\ell 12S}$) of the ply (unidirectional composite). An integration method can be evolved to account for the five distinct ply strengths (author's unpublished notes). However, this method does not include the restraining effects of adjacent plies and thus overpenalizes the random composite strength. As a result of this discussion the following general observation can be made. An integration method which is based on the unidirectional composite only has inherently three disadvantages: (1) it does not account for adjacent ply strengthening effects; (2) it does not utilize the proven laminate theory; and (3) it requires numerical integration.

The failure stress is plotted against FVR for applied tensile, compressive and shear stresses in figure 14 for random boron/epoxy composite, and figure 15 for S-glass/epoxy.

The two important points to be noted from the results in these figures are: (1) boron/epoxy composites attain a maximum strength at FVR which is different for each applied stress. Also an optimum FVR exists for these composites if they are to be subjected to both tensile and compressive loads (fig. 14); and (2) random S-glass/epoxy composites are quite inefficient when compared to the unidirectional composite longitudinal strength (table I and fig. 15).

Comparing strength values from table I with corresponding FVR values in figures 13 to 15 leads to the conclusion that no unique strength ratio of the form random-composite-strength/unidirectional-composite-longitudinal-tensile-strength exists. This ratio appears to vary between 10 and 40 percent.

RESIDUAL STRESSES

A residual stress state is inherent in PRRFC. This residual stress state is a result of the fabrication process and depends on the composite processing and use temperature difference (ref. 20). Invoking the pseudoisotropic analogy, the procedures described in reference 20 can be used to predict the residual stress state in PRRFC.

The residual stresses in the random composite systems investigated herein are plotted against FVR in figure 16. The sense of the residual stress is shown in the schematic in the figure. The residual transverse stress is tensile and the longitudinal is compressive. However, they both are of equal magnitude. The residual stresses in figure 16 are for temperature differences of 300° F for all composites. As can be seen in this figure the residual transverse stresses are significant; they attain magnitudes comparable to corresponding ply strengths (see $S_{\ell 22T}$ values in table I).

The presence of residual stresses in PRRFC will effect their load carrying ability depending on several factors: relative temperature difference, type of applied stress and amount of residual stress relaxation. Specific cases can be investigated as is described in reference 21.

TENSILE IMPACT

The tensile impact resistance of PRRFC can be estimated using concepts advanced in reference 22. Plots of impact energy density (IED) against FVR are shown in figure 17 for the composite systems investigated herein.

It can be seen from the results in figure 17 that random boron/epoxy composites are efficient at FVR less than 0.5 while the Thornel-50S/epoxy composites are efficient at FVR greater than 0.5. The decrease of impact resistance of the boron/epoxy composite after 0.4 FVR is due to the rapid decreases in its ply transverse and intralaminar shear strengths with increasing FVR. See also reference 22.

SPECIFIC PROPERTIES

In feasibility studies and preliminary designs, the specific properties (property/weight-density) are of interest. Plots of specific modulus, tensile strength and tensile impact against FVR are shown in figures 18 to 20, respectively, for the composite systems investigated herein.

The results in these figures indicate that PRRFC should be made from either low FVR (less than about 0.5) boron/epoxy or from high FVR (greater than 0.55) Thornel-50S/epoxy for tensile strengths or tensile impact requirements. On a specific modulus (fig. 18) basis, both boron/epoxy and Thornel-50S/epoxy are about of equal merit.

STRENGTH ESTIMATION

It is possible to predict the failure stress in pseudoisotropic composites when the margin of safety (M.S.) of the most critically stressed ply is known. This is done in the following way. Assume that the composite stress (σ_c) causes the i^{th} ply to be most critically stressed. The M.S. of the i^{th} ply is defined by

$$M.S. = 1 - F(\sigma_c, S_\ell, K_\ell, K'_\ell, \theta) \tag{1}$$

$F(\sigma_c, S_\ell, K_\ell, K'_\ell, \theta)$ is the combined-stress strength function (refs. 16 and 18).

The composite stress (S_c) required to fail the most critically stressed ply and, therefore, the pseudoisotropic composite strength is given by

$$S_c = \frac{\sigma_c}{\sqrt{M.S.}} \qquad \text{if} \quad M.S. \neq 0 \tag{2}$$

$$S_c = \sigma_c \qquad \text{if} \quad M.S. = 0 \tag{3}$$

Invoking the pseudoisotropic laminate analogy, equations (2) and (3) are applicable to PRRFC. The following example illustrates the procedure. Given: the pseudoisotropic composite [0, +45, -45, 90, 90, -45, +45, 0]

$$\sigma_c = 25\ 000 \text{ psi tensile}$$

$$0^\circ \text{ - ply most critically stressed ply}$$

$$M.S. = 0.198$$

$$S_c = \frac{\sigma_c}{\sqrt{M.S.}} = \frac{25\ 000}{\sqrt{0.198}} = 56\ 200 \text{ psi}$$

Therefore, the tensile strength of the PRRFC equals 56 200 psi.

CONCLUSIONS

1. The most common design properties of planar randomly reinforced composites (PRRFC) can be predicted using the pseudoisotropic-laminate analogy.

2. When strength is the controlling design variable, only those fiber/matrix combinations should be considered whose random composite strength is greater than any other material from the same matrix family.

3. The failure strengths of randomly reinforced boron/epoxy composites attain a maximum with respect to fiber volume ratio. The maximum strength fiber-volume-ratio is different for tensile, compressive and shear loads.

4. Randomly reinforced composites have residual stresses due to fabrication processes. The residual stresses will affect the load carrying ability of the PRRFC depending on their specific application.

5. The impact energy density of randomly reinforced isotropic fiber/matrix composites decreases with increasing fiber content, in general, while it increases for those made using anisotropic fibers.

6. The random composite modulus is approximately one-third of the unidirectional composite longitudinal modulus in composites with (E_f/E_m) ratios greater than 20. The corresponding strength varies from about 10 to 40 percent.

APPENDIX - SYMBOLS

E	normal modulus
F	combined-stress strength function
G	shear modulus
H	heat capacity
K	heat conductivity
K_{ℓ}	coefficient in the combined-stress strength function
K'_{ℓ}	empirical factor in the combined-stress strength function
S	strength (failure stress), subscripts identify type
α	thermal coefficients of expansion
θ	ply orientation angle
ν	Poisson's ratio
σ	stress, subscripts identify type

Subscripts:

C	compression
c	composite property
f	fiber property
ℓ	ply or unidirectional composite property
m	matrix property
S	shear
T	tension
1,2,3	material axes directions
α	T or C (tension or compression)
β	T or C (tension or compression)

TABLE I. - TYPICAL PROPERTIES OF UDC AS PREDICTED BY MICROMECHANICS

[Data from ref. 16; fiber volume ratio = 0.5; zero voids; U.S. customary units.]

Property	Units	Boron/ epoxy	Thornel 50S/ epoxy	S-glass/ epoxy
ρ	$lb/in.^3$	0.064	0.052	0.065
H_{ℓ}	$Btu/lb/^oF$	.290	.204	.195
$K_{\ell 11}$	$Btu/hr/ft^2/(^oF/in.)$	12.0	291	4.61
$K_{\ell 22}$	$Btu/hr/ft^2/(^oF/in.)$	3.96	3.72	2.75
$\alpha_{\ell 11}$	10^{-6} in./in./^oF	3.07	-0.121	3.93
$\alpha_{\ell 22}$	10^{-6} in./in./^oF	16.3	23.2	16.1
$E_{\ell 11}$	MPSI	30.3	25.3	6.45
$E_{\ell 22}$	MPSI	1.8	0.96	1.50
$G_{\ell 12}$	MPSI	0.82	.63	.87
$\nu_{\ell 12}$	Ratio	.25	.25	.26
$S_{\ell 11T}$	KSI	195	116	234
$S_{\ell 11C}$	KSI	192	96	180
$S_{\ell 22T}$	KSI	8.1	6.6	8.1
$S_{\ell 22C}$	KSI	28.4	19.1	30.1
$S_{\ell 12S}$	KSI	12.1	7.5	9.1
$K_{\ell 12}$	Ratio	0.94	1.37	0.75
$K'_{\ell 12\alpha\beta}$ (α,β = T,C)	Ratio	1.0	1.0	1.0

REFERENCES

1. Toth, L. W.; and Boller, T. J.: Manufacturing Concepts in Application of Molded Advanced Composites to Aerospace Components. Aircraft Structures and Materials Application. Western Periodicals Co., 1969, pp. 361-368.

2. Lee, Lieng-H.: Strength-Composition Relationships of Random Short Glass Fiber-Thermoplastics Composites. Polymer Eng. Sci., vol. 9, no. 3, May 1969, pp. 213-224.

3. Cox, H. L.: The Elasticity and Strength of Paper and Other Fibrous Materials. Brit. J. Appl. Phys., vol. 3, Mar. 1952, pp. 72-79.

4. Gordon, J. E.: On the Present and Potential Efficiency of Structural Plastics. J. Roy. Aeron. Soc., vol. 56, Sept. 1952, pp. 704-728.

5. Cook, J.: The Elastic Constants of an Isotropic Macrix Reinforced with Imperfectly Oriented Fibers. J. Phys., Pt. D, Brit. J. Appl. Phys., SER. 2, vol. 1, no. 6, June 1968, pp. 799-812.

6. Dodson, C. T. J.: A New Approach to the Fracture of Bonds in a Random Fibrous Network Such as Paper. Brit. J. Apply. Phys., vol. 18, Aug. 1967, pp. 1199-1204.

7. Tsai, Stephen W.; and Pagano, Nicholas J.: Invaniant Properties of Composite Materials. Composite Materials Workshop. S. W. Tsai, J. C. Halpin, and N. J. Pagano, eds., Technomic Publishing Co., 1967, pp. 233-253.

8. Nielsen, L. E.; and Chen, P. E.: Young's Modulus of Composites Filled with Randomly Oriented Fibers. J. Materials, vol. 3, no. 2, June 1968, pp. 352-358.

9. Lees, J. K.: A Study of the Tensile Modulus of Short Fiber Reinforced Plastics. Polymer Eng. Sci., vol. 8, no. 3, July 1968, pp. 186-194.

10. Lees, J. K.: A Study of the Tensile Strength of Short Fiber Reinforced Plastics. Polymer Eng. Sci., vol. 8, no. 3, July 1968, pp. 195-201.

11. Bolotin, V. V.: Theory of Reinforced Layered Medium with Random Initial Irregularities. Mekh. Polim., no. 2, 1966, p. 11.

12. Halpin, J. C.; and Pagano, N. J.: The Laminate Approximation for Randomly Oriented Fibrous Composites, J. Composite Materials, vol. 3, Oct. 1969, pp. 720-724.

13. Halpin, J. C.; Jerine, K.; and Whitney, J. M.: The Laminate Analogy for 2 and 3 Dimensional Composite Materials. J. Composite Materials, vol. 5, Jan. 1971, pp. 36-49.

14. Anderson, R M.; and Lavengood, R. E.: Variables Affecting Strength and Modulus of Short Fiber Composites. SPE J., vol. 24, Mar. 1968, pp. 20-26.

15. Lekhnitskii, S. G. (P. Fern, trans.): Theory of Elasticity of an Anisotropic Elastic Body. Holden-Day, Inc., 1963.

16. Chamis, Christos C.: Computer Code for the Analysis of Multilayered Fiber Composites - Users Manual. NASA TN D-7013, 1971.

17. Anon.: Integrated Research on Carbon Composite Materials. Part 1. Union Carbide Corp. (AFML-TR-66-310, pt. 1, AD-803525), Oct. 1966.

18. Chamis, C. C.: Failure Criteria for Filamentary Composites. Composite Materials: Testing and Design. Spec. Tech. Publ. 460, ASTM, 1969, pp. 336-351.

19. Chen, P. E.: Strength Properties of Discontinuous Fiber Composites. Polymer Eng. Sci., vol. 11, no. 1, Jan. 1971, pp. 51-56.

20. Chamis, Christos C.: Lamination Residual Stresses in Multilayered Fiber Composites. NASA TN D-6146, 1971.

21. Chamis, Christos C.: Lamination Residual Stresses in Cross-Plied Fiber Composites. Proceedings of the 26th Society of the Plastics Industry Annual Technical Conference, 1971, pp. 17-D1 - 17-D12.

22. Chamis, Christos C.; Hanson, Morgan P.; and Serafini, Tito T.: Designing for Impact Resistance with Unidirectional Fiber Composites. NASA TN D-6463, 1971.

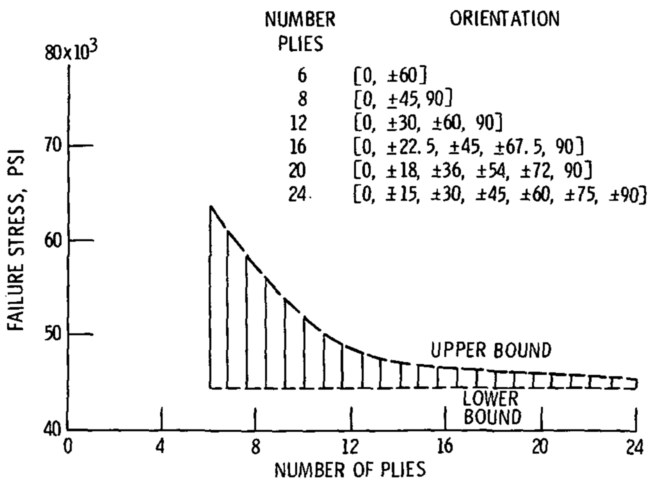

Figure 1. - Upper and lower bounds for strength of various pseudo-isotropic composites from Modmor-I/epoxy at 0.50 fiber volume content, zero voids and no residual stress.

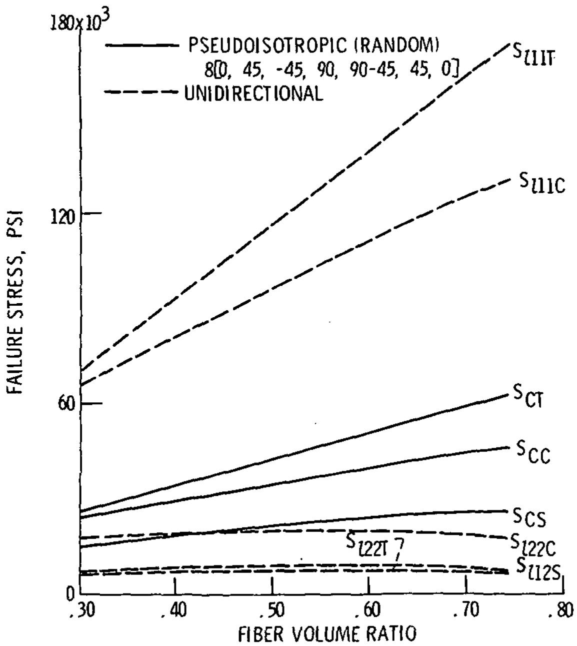

Figure 2. - Comparison of pseudoisotropic (random) and unidirectional composite failure stresses for Thornel-50S/epoxy with zero voids and no residual stresses.

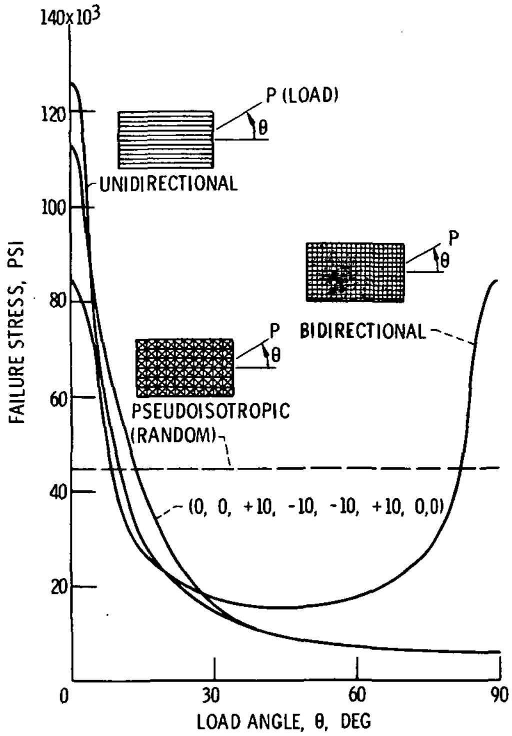

Figure 3. - Failure stresses for special fiber composites. (Modmor-I/epoxy. Fiber volume ratio = 0.5, zero voids and no residual stresses).

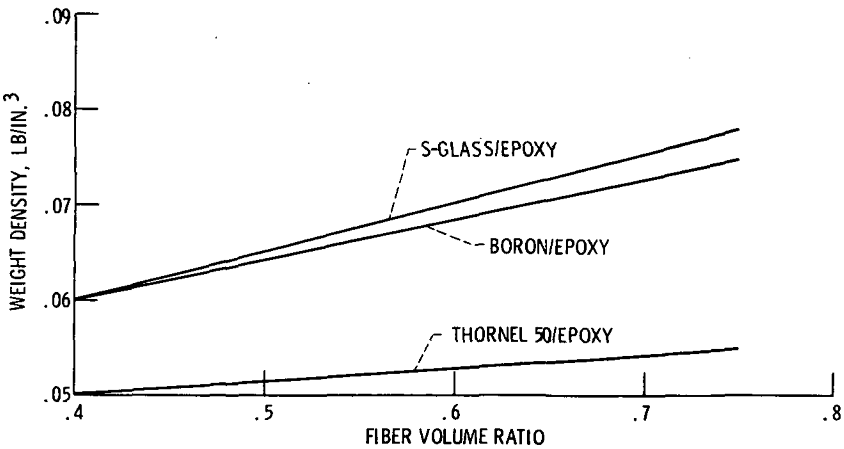

Figure 4. - Weight density for pseudoisotropic (random) fiber composites (zero voids).

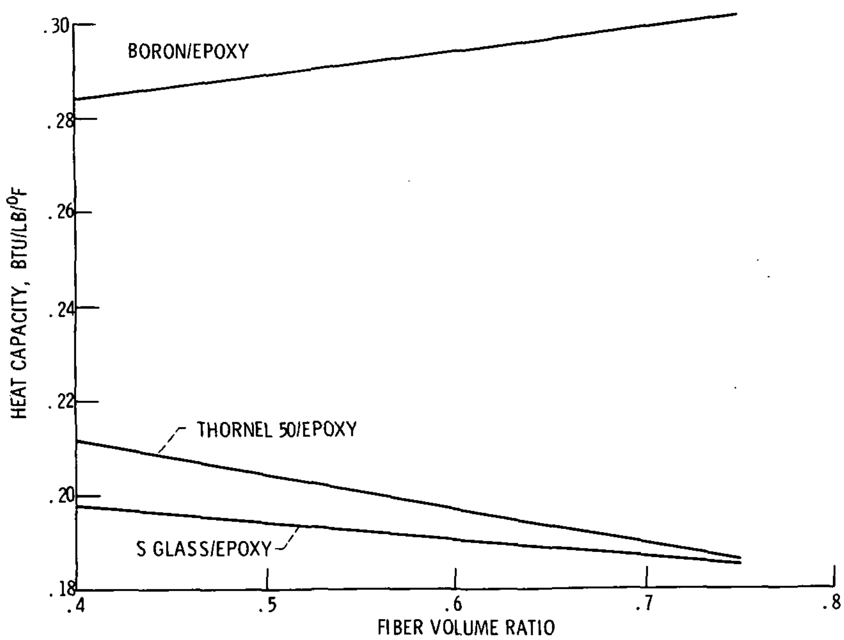

Figure 5. - Heat capacity for pseudoisotropic (random) fiber composites (zero voids).

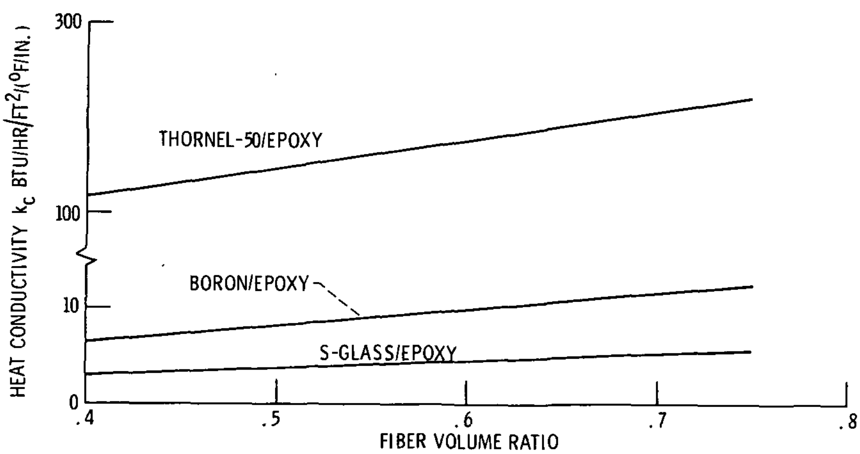

Figure 6. - Inplane heat conductivity for pseudoisotropic (random) fiber composites (zero voids).

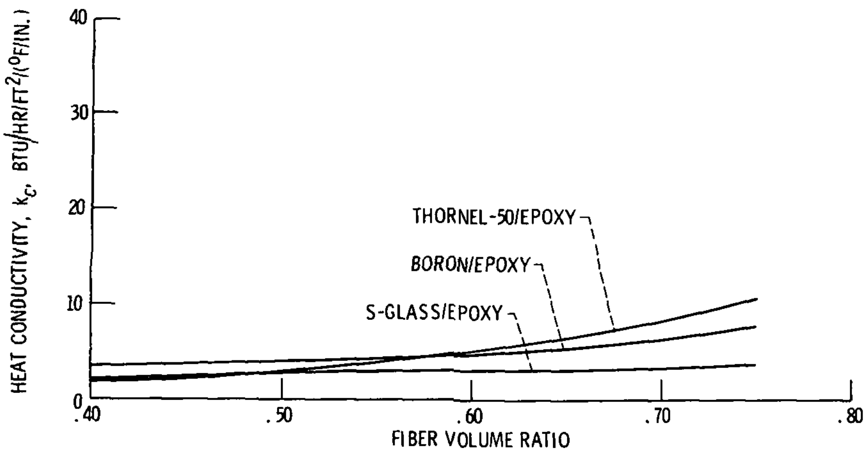

Figure 7. - Through thickness heat conductivity for pseudoisotropic (random) composites (zero voids).

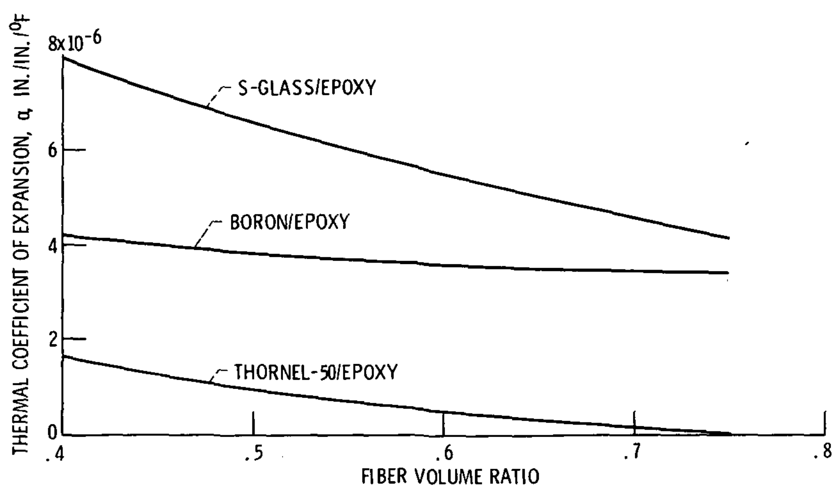

Figure 8. - Inplane thermal coefficients of expansion for pseudoisotropic (random) fiber composites (zero voids).

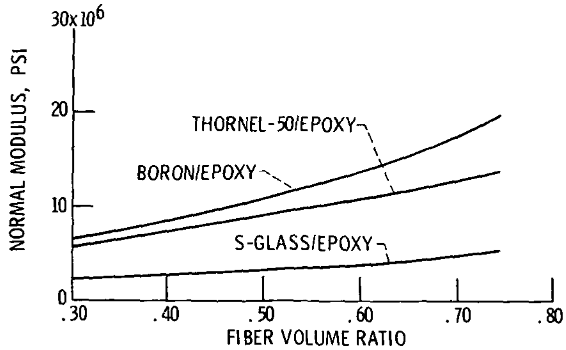

Figure 9. - Normal moduli of pseudoisotropic (random) fiber composites (zero voids).

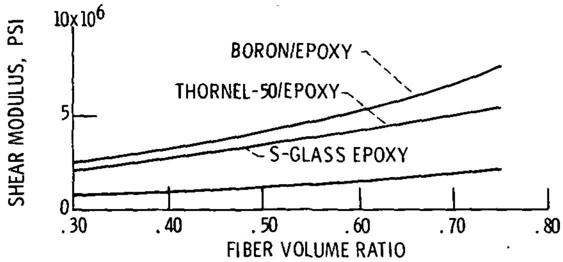

Figure 10. - Shear moduli of pseudoisotropic (random) fiber composites (zero voids).

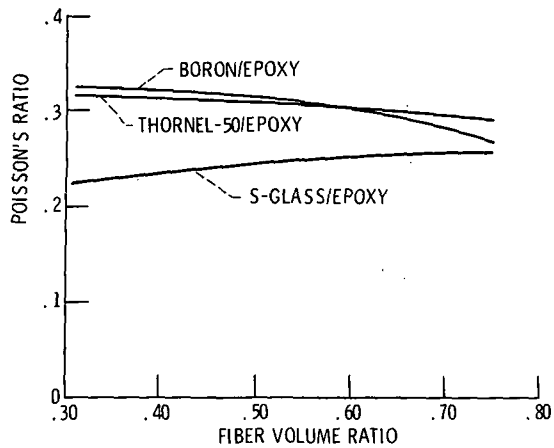

Figure 11. - Poisson's ratios of pseudoisotropic (random) fiber composites (zero voids).

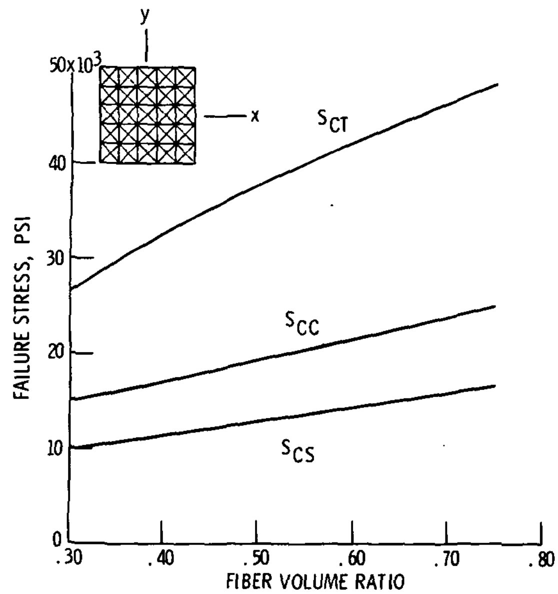

Figure 12. - Failure stresses for pseudoisotropic (random) Thornel-50/epoxy composites. No voids and no residual stress.

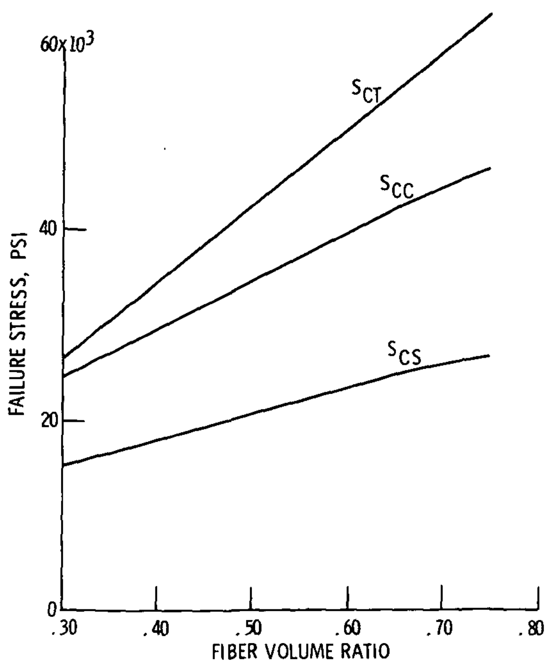

Figure 13. - Failure stresses for pseudoisotropic (random) Thornel-50 S/epoxy composites. No voids and no residual stress.

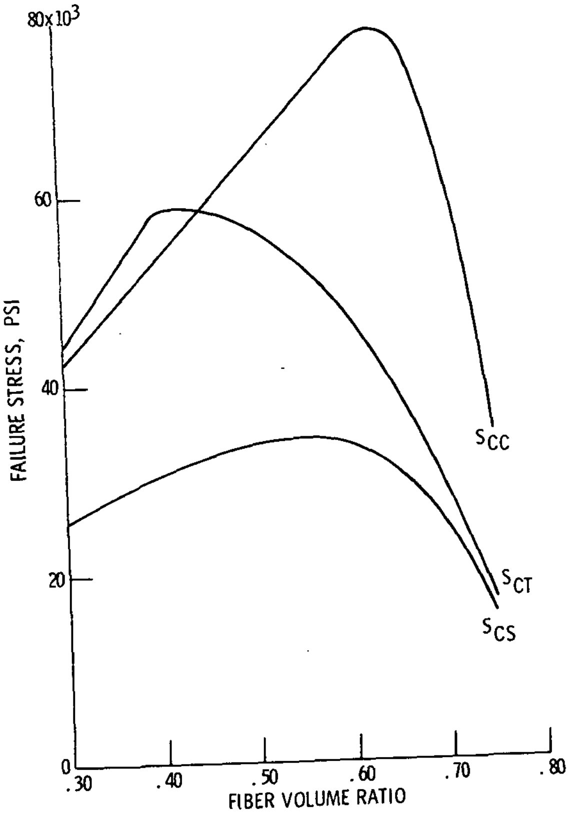

Figure 14. - Failure stresses for pseudoisotropic (random) boron/epoxy composites. No voids and no residual stress.

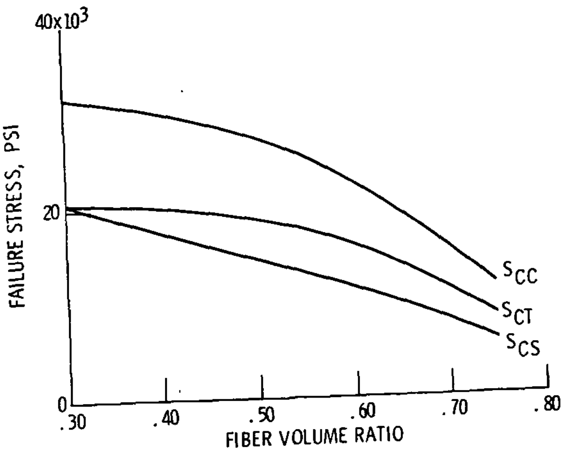

Figure 15. - Failure stresses for pseudoisotropic (random) S-glass/epoxy composites. No voids and no residual stress.

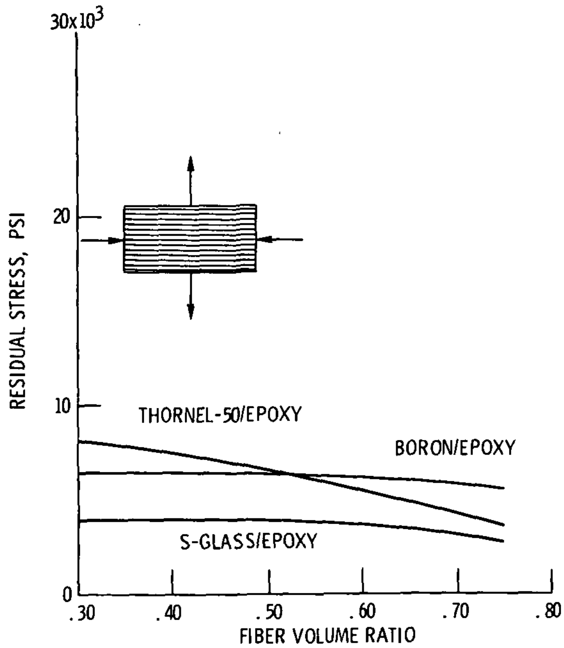

Figure 16. - Ply residual stresses in pseudoisotropic (random) fiber composites. Temperature difference: 300° F. Residual stress magnitude same in all plies. Sense as shown in sketch.

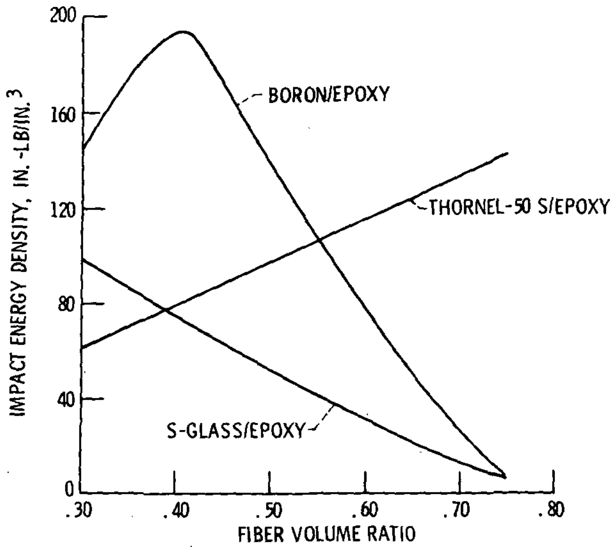

Figure 17. - Tensile impact energy density to initial damage for pseudoisotropic (random) fiber composites. No voids and no residual stress.

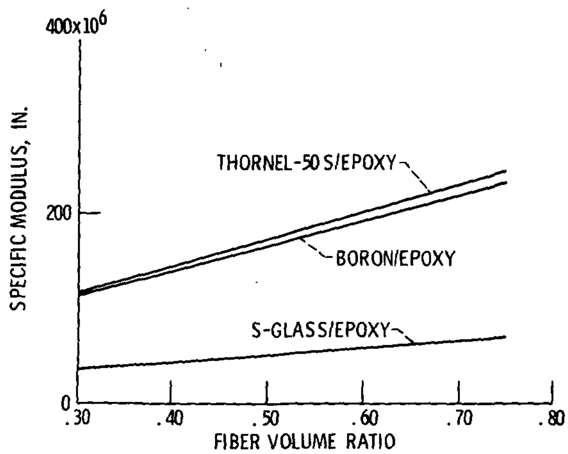

Figure 18. - Specific moudlus for pseudoisotropic (random) fiber composites (zero voids).

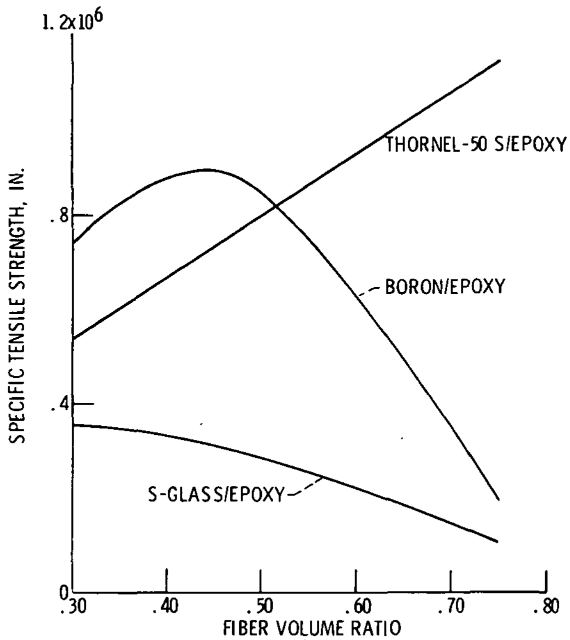

Figure 19. - Specific tensile strengths for pseudoisotropic (random) fiber composites. No voids and no residual stress.

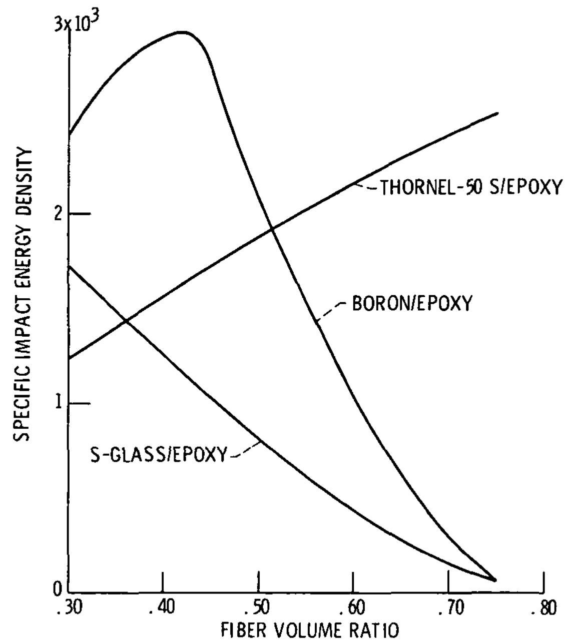

Figure 20. - Specific tensile impact energy density to initial damage for pseudoisotropic (random) fiber composites. No voids and no residual stress.

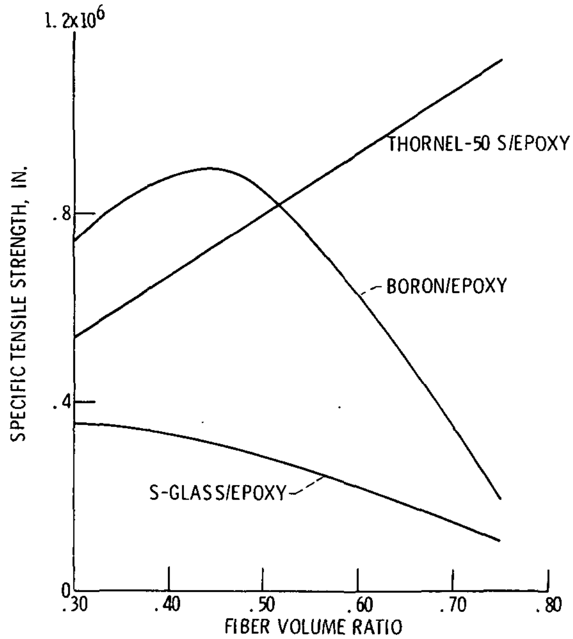

Figure 19. - Specific tensile strengths for pseudoisotropic (random) fiber composites. No voids and no residual stress.

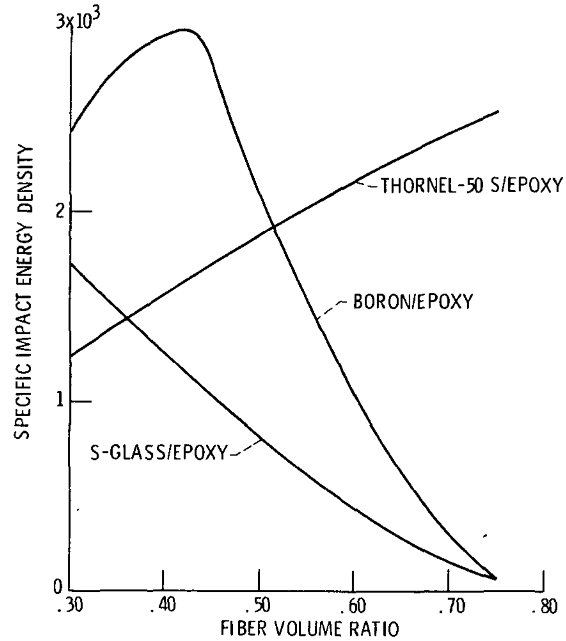

Figure 20. - Specific tensile impact energy density to initial damage for pseudoisotropic (random) fiber composites. No voids and no residual stress.